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A method for determining the financial cost of damage to buildings caused by seismic ground vibrations

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Abstract

A method for determining the value of the damage to a single-family residential building located near an open-pit mine caused by ground vibrations is presented. The article describes how to objectively determine the degree of actual wear and tear to a residential building (Zr) affected by ground vibrations created during rock mining using blasting. It consists of the method of "weighted average degree of technical wear and tear of individual elements" known from literature and used to calculate the actual wear and tear of the building. The natural wear and tear of the building is then calculated from dependences given in the literature. The percentage of the building's natural wear and tear (Zn) is subtracted from the percentage of the building's actual wear and tear. As a result of the subtraction, a percentage of accelerated wear and tear of the building (Zb), which is caused by vibrations of the ground during rock blasting, is obtained. Multiplying the percentage of accelerated wear and tear of the building by the value of a new building gives a value of the damage caused by ground vibrations. Examples of determining the value of the damage caused by ground vibrations in practice are described.

Keywords: sejsmic vibrations, natural wear of the house, accelerated wear of the house, cost of repairing

1. Introduction

In surface mining, conducting works with the use of explosives leads to the formation of seismic vibrations, which may have a harmful effect on local buildings. Blasting in rocks in an opencast mine with explosives causes vibrations of the rock and subsequently the ground around it. These vibrations can be harmful to the road and residential infrastructure through the propagation of seismic waves in all directions. It has been determined (Duval, Nicholson, Johnson, 1971) that the magnitude of the harmful effect of vibration in a given area depends on the size of the mass of the explosive charge and the distance between the mine and the object in question. Parameters that enable comparisons of the value of individual vibrations caused by blasts include amplitude, speed and acceleration of vibrations at the measuring point and the corresponding frequency. These parameters are associated with the geological and tectonic conditions of the passing wave, see Fig. 1, and consequently with the blasting site resulting from the mining process. This affects the conditions of seismic conductivity both within the exploited deposit and outside it. The magnitude of these parameters affects the types of damage caused in the surrounding residential houses. For a given distance, the size of the damage to houses depends on the house's resistance to shocks and the size of the explosive charge.

2. The mining of rocks with explosives [ME]

To date, in Poland and around the world, it is believed that the vibrations of the medium arising during the mining of rocks with explosives [ME] propagate circularly with the same energy in each direction, just like waves from a stone thrown into the water, and their energy of vibration decreases with distance (Chrzan, Modrzejewski, 2014; Chrzan, Gliński, 1995). Rocks are mined in an open-pit mine by blasts in the rock block. Block dimensions are at a length dependent upon the number of holes in the row, the width is dependent upon the number of rows, and the height is dependent upon the length of the almost vertical holes located in series on the surface of the rock block. These holes are filled with explosive material, which causes vibrations in the rock during the explosion and then in the soil outside the deposit. So far, it is assumed that the value (Bakalarz, 2002; Chrzan, Modrzejewski, 2014; Chrzan, Gliński, 1995) of rock mining parameters – i.e. the amplitude of deflection of a medium molecule from its equilibrium position and the speed and acceleration Onderka (1971) of the vibrating of the medium – depends on the size of the ME charge being fired and the distance between the mine and the given point. With the maximum permissible values of deflection amplitude and velocity and acceleration of particles of a given medium, the minimum safe distance from the explosion site for single-family residential buildings shall be determined on the basis of Polish Standard (2016). Ground vibrations caused by an explosion in a nearby open-pit mine can spread to the building causing accelerated wear. This wear is expressed by various types of damage to the building, such as the cracking and falling of plasters and the cracking of partition walls, ceilings and bearing walls.

The problem is that the same damage occurs in buildings that are not near the opencast mine of rock raw materials during their natural wear but over a much longer period of operation. No one can unequivocally state that one specific crack was caused by the natural wear of the building and the other because of vibrations caused by the excavation of rock in a nearby quarry. There is currently no method that would accurately and objectively determine what percentage of building damage is the result of ground vibrations created during the use of explosives in the rock opencast mine and how to convert it to the value of the damage caused in the building. The current method of determining damage to a residential building caused by ground vibrations during blasting consists of comparing two similar houses. One of the houses is further away

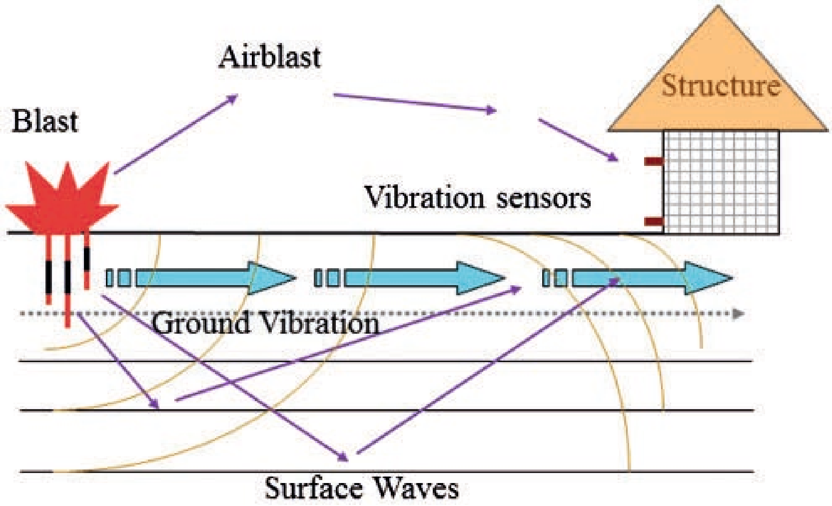

Fig. 1. Schematic illustration of factors influencing accelerated house wear near the quarry (Zhou, Shi, Li.2015)

(e.g. 2000 m) from the quarry and the damage recorded there is not included in the damage caused by blasting in the house next to the quarry. The assessor, using their knowledge and experience, analyses the damage and subjectively determines which cracks are caused by ground vibrations and which arose due to reasons of the natural exploitation of the house. On this basis, he determines the percentage of damage that has occurred to the house due to vibrations caused by quarry blasting and makes a list of these with characteristics. Using the construction catalogue of material expenditure/ KNR-Polish acronym for the name/ determines the cost of materials and the labour necessary to remove them, and thus determines the costs of damage suffered. A method based on Polish building standard (2016) PN-B-02170:2016-12 is also used, based on which, measured on the building during rock mining vibration speed, it can be assessed what damage to the house can occur. On the basis of the above--mentioned Polish Standard, the assessor, in accordance with his knowledge and experience, analyses the damage and subjectively determines what damage has occurred due to ground vibrations and makes a list with their characteristic.

Using the construction catalogue showing material prices, the costs of materials and the labour necessary to remove them are determined and the cost of the damage suffered is established. The disadvantage of this method is that it requires a research team equipped with measuring apparatus and allows for the inclusion of wall cracks resulting from uneven foundation settlement, i.e. natural wear and tear as an effect from ground vibration. The cost of such an assessment also constitutes a significant part of the cost of the damage caused. Sometimes, the open-pit mine wants to pay the owner of the house for damages done to it, but the costs assessed as described above are not objectively documented and justified. The disadvantage of the current methods of determining the value of the damage is the subjective assessment and the failure to take into account the percentage of natural wear and tear to the building. An objective determination of the cost of damage is needed by taking into account the percentage of accelerated building wear caused by ground vibrations due to blasts in the quarry and defined as the difference between the actual building wear and the building's natural wear. The described method was implemented by assuming that the actual consumption of a residential building, as well as accelerated building wear caused by ground vibrations generated during mining operations and natural wear, are assessed on the basis of the percentage of building consumption. The usual construction method for determining the actual consumption of a building is made under the following assumptions (Drozd, 2017; Michalik, 2014; Szykulska, n.d.). Buildings are composed of many elements that wear out (lose their utility and strength values e.g. due to cracks) at various rates. Therefore, to determine the degree of actual wear of the building (with the participation of vibrations), one should, belongs:

a) divide the object into "i-th" elements,
b) determine the percentage share of the costs of individual elements Ai in the cost of the entire new object A (%),
c) assess the degree of wear of individual elements of the house after an inspection, Srz.i, according to the tables used in construction (Szykulska, n.d.),
d) determine the weighted average degree of real consumption of the entire building structure. The weighted average degree of actual consumption of the building object Zr (in percent) is defined as the product of the sum (Ai × Srz.i) × 100% of all its elements.

An objective method for determining the actual wear and tear of a residential building (Zr) damaged by ground vibrations is to use the technical wear and tear of individual building clements. It is based on the fact that, known from the literature (Drozd, 2017; Michalik, 2014; Szykulska, n.d.) using the "weighted average" method, the degree of technical wear of individual elements is the product of the actual wear of individual building elements (Srz.i) and the percentage value of these elements (Ai) in relation to the whole building expressed as a percentage. In this way, the value of the actual percentage building wear (Zr) is obtained. The natural (Zn) building wear percentage is subtracted from the actual building wear percentage. This gives the accelerated building wear percentage (Zb) caused by ground vibration. The damage value caused by ground vibrations is equal to the accelerated wear and tear of the building multiplied by the value of a new building in the area However, the natural percentage consumption of a residential building (Zn) (Szykulska, n.d.) is calculated as the current building age (t) in years divided by its lifetime (T) (Szykulska, n.d.) in years. The value of this ratio is squared and then multiplied by 100 to obtain building consumption expressed as a percentage (%) (Krajewska, 2016). The predicted period of durability (Szykulska, n.d.) of the T building in years for masonry, stone, brick and cement mortar, and concrete is 150 years (Podwórna, 2019). For wooden and half-timbered buildings T = 60 years. Therefore, the accelerated percentage consumption of a residential building caused by ground vibrations (Zb) is defined as the difference obtained from subtraction. We subtract the natural consumption (Zn) from the percentage actual consumption (Zr) and get the accelerated building consumption (Zb) due to ground vibrations caused by explosions in the quarry. The advantage of the developed method is the accurate and objective determination of the percentage of real wear of the damaged building, the percentage of natural wear of the residential building and accelerated wear of the building due to ground vibrations. The financial cost of damage incurred in the building, expressed by the accelerated percentage consumption of the building (Zb) damaged by ground vibrations is equal to the product of the value of the new building (Wb) multiplied by the accelerated percentage of consumption of the of residential building (Zb), which is the difference between the percentage of actual consumption (Zr) and the percentage of natural consumption (Zn). The advantage of the given method is the accurate financial determination of the amount needed to remove the damage caused to a residential building by ground vibrations. The developed method is explained using two examples.

Example I

The percentage of the consumption (Zr) of a residential building built from brick and cement mortar and currently 50 years old is calculated as the sum of the products of the actual consumption of the individual (Srz.i) building components (i) and the percentage value of these elements (Ai) in relation to the whole building multiplied by 100.

The actual consumption (Srz.i) of the individual components (Ai) for a building 600 m from the quarry, when excavating rock with a charge of explosives of Qc = 5000 kg is given in Table 1: By calculating the products Srz i and Ai, we obtain the value of the actual percentage of building consumption (Zr) in per cent, which is:

Table 1. Determination of the percentage of building wear and tear according to the weighted average method – sample table of integrated elements (Michalik, 2014)

Element number	Combined elements of a building	Share of an element in the cost of the object Ai [%]	Degree of technical wear and tear of an element Srz.i [%]
A1	Foundations, ceilings, stairs,	30	50
A2	Walls, partitions, roof	50	25
A3	Central heating installation, plumbing installation, electrical installation	10	75
A4	External and internal plasters, floors	5	50
A5	Window and door woodwork, floors	5	25

$$Zr = [(A1 \times Srz.\ 1) + (A2 \times Srz.\ 2) + (A3 \times Srz.\ 3) + (A4 \times Srz.\ 4) + (A5 \times Srz.\ 5)] \times [100]\ (\%),$$

$$Zr = [(0.30 \times 0.50) + (0.50 \times 0.25) + (0.10 \times 0.75) + (0.05 \times 0.5) + (0.05 \times 0, 25)] \times [100] = 38.7\ (\%).$$

The value of natural consumption (Zn) of a building currently t = 50 years old with a durability period of T = 150 years is calculated as follows. The current age (t) of the building in years is divided by its lifetime (T) in years and the resulting value of this division is squared and then multiplied by 100, obtaining the wear and tear of the building in percentage (Zn).

$$Zn = (t / T)^2 \times 100\ (\%),$$

$$Zn = (50/150)^2 \times 100 = 11.1\ (\%).$$

The calculated (Zb) accelerated percentage consumption of a single-family residential building damaged by ground vibrations generated during rock excavation by firing with a load mass of Qc = 5000 kg is the difference between the value of the percentage of actual consumption (Zr) and the value of the percentage of natural consumption of the building (Zn) and is:

$$Zb = 38.7 - 11.1 = 27.6\ (\%).$$

Fig. 2. Cracking and falling plaster from a vertical interior wall (own archive)

This allows us to determine the accelerated percentage consumption of a single-family house arising during the excavation of rocks with explosives in an opencast mine with an accuracy of 0.1%.

The example given shows that a charge of explosives value of Qc = 5000 kg causes the accelerated percentage consumption of a single-family house located at a distance of 600 m from the mine with a value of 27.6%. It can therefore be determined with an accuracy of 0.1% that the average damage cost is 27.6 ±0.1% of the building value. The example building value is 100,000.00 $ and represents the average cost of constructing the same but new buildings in the area and in the year in which the percentage use of the building is assessed. Thus, the owner of the mine caused damage to the building, the cost of which is 27.6% × 100,000.00 $ = 276,800.00 $. This sum should be paid to the owner of a single-family building located 600 m from the open--pit mine as a compensation sum due to damage to the building caused by the owner of the open-pit mine. This is the cost of restoring the property to its pre destruction condition (Szykulska, n.d.), i.e. the replacement value of the home.

Example II

The value (Zr) of the actual percentage consumption of a residential building built of brick and cement mortar and currently 50 years old is calculated as the sum of the products (Srz.i) of the actual consumption of the individual building components (i) and the percentage value of these elements (A) in relation to the whole building multiplied by 100.

Table 2. Determination of the percentage of building wear and tear according to the weighted average method. Sample table of integrated elements (Michalik, 2014)

Element number	Combined elements of a building	Share of an element in the cost of object Ai [%]	Degree of technical wear and tear of an element Srz.i [%]
A1	Foundations, ceilings, stairs,	30	25
A2	Walls, partitions, roof	50	10
A3	Central heating installation Plumbing installation Electrical installation	10	25
A4	External and internal plasters, floors	5	30
A5	window and door woodwork, floors	5	10

Actual consumption (Srz.i) of individual components (Ai) with the same building as in Example I, when cutting rocks by firing a charge of explosives value of Qc = 5000 kg but located 900 m from the quarry further than the building in Example I is:

- Srz.1 (A1) – 25% = 0.25;
- Srz.2 (A2) – 10% = 0.10;
- Srz.3 (A3) – 25% = 0.25;
- Srz.4 (A4) – 30% = 0.3;
- Srz.5 (A5) – 10% = 0.10.

The percentage value (Ai) of these elements in relation to the whole building is:

- Element: A1 – 30% = 0.3 – foundations, ceilings, stairs;
- Element: A2 – 50% = 0.5 – walls, partitions, roof;
- Element: A3 – 10% = 0.1 – installations;
- Element: A4 – 5% = 0.05 – external and internal plasters, floors;
- Element: A5 – 5% = 0.05 – window and door woodwork, floors.

By calculating the products (Srz.i) and (Ai) we get the value of the actual percentage of building consumption (Zr) in (%), which is:

$$Zr = [A1 \times S.1\,(A1) + A2 \times S.2\,(A2) + A3 \times S.3\,(A3) + A4 \times S.4\,(A4) + A5 \times S.5\,(A5)] \times [100]\ (\%)$$

$$Zr = [(0.30 \times 0.25) + (0.50 \times 0.10) + (0.1 \times 0.25) + (0.05 \times 0.30) + (0.05 \times 0{,}10)] \times [100] = 17.0\ (\%)$$

The value of natural consumption (Zn) of a building with t – 50 years old with a durability period of T = 150 years [10] is calculated as the current age of the building (t) in years divided by its lifetime (T) in years and the resulting value of this ratio is squared and then multiplied by 100 to obtain the building's consumption expressed as a percentage:

$$Zn = (t/T)^2 \times 100\ (\%),$$

$$Zn = (50/150)^2\ 100 = 11.1\ (\%).$$

The percentage of accelerated wear of a detached house (Zb) as a result of ground vibration generated during rock excavation by firing an explosive charge mass Qc = 5000 kg located further away from the quarry than the building in Example 1 has been calculated. The accelerated wear of the detached house is

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Fig. 3. Scratch marks on plaster on a vertical interior wall (own archive)

the difference between the percentage of actual wear (Zr) and the percentage of natural wear of the building (Zn) and is; (Zr) in (%) i.e.;

$$Zb = 17.0 - 11.1 = 5.9\ (\%).$$

This allows us to determine, with 0.1% accuracy, the accelerated percentage of building consumption arising during the excavation of rocks in an opencast mine with the use of explosives. It can therefore be determined with an accuracy of 0.1% that the average damage cost is 5.9% of the building value. The given example shows that a residential house 900 m from the opencast mine has an accelerated percentage consumption of 5.9% compared to natural consumption. The example building value is 100,000.00 $ and represents the average cost of constructing the same but new buildings in the area and in the year in which the percentage use of the building is assessed. Thus, the owner of the mine caused damage to the building, the cost of which is 5.9% × 100,000.00 $ = 5,900.00 $. This sum should be paid to the owner of a residential building located 900 m from the open-pit mine as compensation for damage caused to the building by the owner of the open-pit mine. This is the cost of restoring the property to its condition before vibration damage (Krajewska, 2016), i.e. the replacement value of the house.

3. Summary

The examples show that an explosive charge of Qc = 5000 kg causes accelerated wear and tear on a residential building 600 m and 900 m from a mine. The method of objectively determining the accelerated percentage of single-family building consumption caused by ground vibrations during rock mining using explosives has been presented and described with examples.

The financial cost of restoring a building (Zb), damaged due to ground vibrations to its undamaged state expressed (Krajewska, 2016) by the accelerated percentage wear and tear of a building (Zb). This cost is equal to the product of the value of the new building and the percentage of accelerated wear of the residential building.

References

Bakalarz, A. (2002). Ocena okresu użytkowania elementów i obiektów budowlanych do celów projektowych. *Zeszyty Naukowe Politechniki Śląskiej*, *95*.

Chrzan, T., Modrzejewski, S. (2014). Prognozowanie wartości drgań parasejsmicznych szkodliwie działających na infrastrukturę drogową i mieszkalną. *Logistyka*, *5*, 222–232.

Chrzan, T., Gliński, J. (1995). Stan i kierunki przemian w określaniu promienia strefy szkodliwości drgań sejsmicznych. In *VI Krajowy Zjazd Górnictwa Odkrywkowego* (pp. 73–82). Konin.

Drozd, W. (2017). Metody oceny stanu technicznego budynków w aspekcie ich praktycznego zastosowania. *Przegląd Budowlany*, *4*, 43–47.

Duvall, W.I., Johnson, Ch.F., Nicholls, H.R. (1971). *Blasting vibrations and their effects on structures.* U.S. Department of the Interior, Bureau of Mines.

Krajewska, M. (2016). Przydatność wybranych sposobów ustalania stopnia zużycia technicznego budynków w wycenie nieruchomości. *Świat Nieruchomości*, 96(2), 63–68.

Michalik, K. (2014). Zużycie techniczne budynków i budowli. Metodologia oceny stanu technicznego budynków i budowli. *Chrzanów: Wydawnictwo Prawo i Budownictwo*.

Onderka, Z. (1971). Badania intensywności drgań sejsmicznych przy strzelaniu metodą otworów wiertniczych w kopalniach odkrywkowych. *Zeszyty Naukowe AGH*, *334*.

PN-B-02170:2016-12. Skala wpływów dynamicznych.

Podwórna, M. (2019). Określanie stanu technicznego obiektu budowlanego w wycenie nieruchomości. In I. Rącka (Ed.), *Nieruchomość w przestrzeni 5. Tom 2: Analiza rynku nieruchomości*. Poznań: Bogucki Wydawnictwo Naukowe, 2019.

Szykulska, B. (n.d.). Retrieved from http://bondi.com.pl/portfolio/okreslanie-zuzycia-obiektow-budowlanych/ (date of access: 2020/12/23).

Zhou, J., Shi, X., Li, X. (2015). Utilizing gradient boosted machine for the prediction of damage to residential structures owing to blasting vibrations of open pit mining. *Journal of Vibration and Control*, *22*(19).

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Metoda określania wartości finansowej szkód w budynkach spowodowanych drganiami sejsmicznymi gruntu

Streszczenie

przedstawiono sposób określania wartości szkody spowodowanej drganiami gruntu w jednorodzinnym budynku mieszkalnym położonym przy kopalni odkrywkowej. W artykule opisano sposób obiektywnego określania procentowego rzeczywistego zużycia budynku mieszkalnego (Zr) uszkodzonego drganiami gruntu powstałymi podczas urabiania skał strzelaniem. Polega on na tym, że sposobem „średnioważonego stopnia zużycia technicznego poszczególnych elementów" (Drozd, 2017; Podwórna, 2019) obliczamy rzeczywiste zużycie budynku. Następnie z podanej literaturowej zależności obliczamy zużycie naturalne budynku. Od rzeczywistego procentowego zużycia budynku odejmuje się naturalne (Zn) procentowe zużycie budynku. W wyniku odejmowania otrzymuje się przyśpieszone zużycie procentowe budynku (Zb) spowodowane przez drgania gruntu powstałe podczas urabiania skał strzelaniem. Mnożąc przyśpieszone zużycie procentowe budynku przez wartość nowego budynku, otrzymuje się wartości szkody spowodowanej drganiami gruntu. Opisano przykłady określania wartości szkody spowodowanej drganiami grunt w praktyce. Podany sposób dotyczy wszelkich drgań działających szkodliwie na budynki mieszkalne.

Słowa kluczowe: drgania sejsmiczne, szkody górnicze, uszkodzone budynki na terenach górniczych